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THE USER REQUIREMENTS FOR AN AIRFIELD PAVEMENT SYSTEM

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Champaign, Illinois

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13. ABSTRACT

Until recently, airfield pavement failure has been taken to mean structural failure. It was generally assumed that once the pavement had failed structurally, it was no longer serviceable. The trend today is away from a structural failure definition and toward the much needed criteria which combine pavement structural responses and functional requirements. Thus, instead of using a purely structural criterion such as the number of cracks as the only failure criterion, functional indices based on user requirements are employed to indicate how well the pavement is fulfilling the intended functional requirements. This assumes that the user and functional requirements can be defined and quantified to provide indices which will prescribe the functional quality of the pavements with respect to the primary elements--the users.

The evolution of a systems approach to the design and evaluation of airfield pavements necessitated the establishment of a set (or sets) of quantified user requirements, which could be used to define the critical parameters of the pavement-aircraft system. This study determined not only the users and the requirements for aircraft-airfield pavements systems, but also generated a hierarchy of users, and delineated the respective needs of the primary users.

14. KEY WORDS

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THE USER REQUIREMENTS FOR AN AIRFIELD PAVEMENT SYSTEM

by

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January 1973

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II

FOREWORD

This study was sponsored by the U.S. Army Corps of Engineers, Office of the Chief of Engineers (OCE) Washington D.C., under Project 4A062112A891 "Permanent Construction Materials and Techniques," Task 02 "Engineering Design Criteria and Technology for Military Facilities," Work Unit 003 "Rational Pavement Design." Mr. Frank Hennion served as technical monitor for OCE.

The study was conducted within the Management Systems Division of the U.S. Army Construction Engineering Research Laboratory (CERL) located in Champaign, Illinois. This report was prepared by Mr. Joseph L. Pfeister.

The author is grateful to the many persons who contributed to the report with review literature and discussions.

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1 INTRODUCTION

Background. Available literature on the subject of airfield pavements reveals that a number of researchers have attempted to list the desirable properties of pavements and pavement surfaces. While these lists provide some insight into the pavements problem, they have not presented comprehensive and systematic description of the user requirements for pavements.[1,2] Obviously, a new approach for defining this problem had to be developed.

On 23 March 1970, the U.S. Army Construction Engineering Research Laboratory (CERL), Champaign, Illinois, held a conference on "Systems Approach to Airfield Pavements," at Allerton Park. At this conference, it was agreed that a new unifying approach to airfield pavement design was needed; and to accomplish this objective, it was necessary to identify the roles and interactions of the groups, activities, and components involved in the pavement design process. Consequently, the CERL Project Systems Branch, under the direction of Dr. E. L. Murphree Jr., designed a basic evaluation model, presented in Figure 1. This evaluation model indicates that the most essential task in developing a systems approach to airfield pavement design and evaluation consists of combining the following three elements: (1) a complete set of quantified user requirements, (2) the dynamic responses of typical aircraft, and (3) the functional characteristics of the pavement.

Purpose and Scope. This study was conducted to define a functional index which will be used in evaluating the performance of airfield pavement systems. In developing a user requirement model, the universe of disciplines affected by the airfield pavement system is defined, and the pertinent elements, characteristics and terms are clearly described. Also, a systematic approach is used to insure that the appropriate and complete set of users is selected.

[1] R.W. Woodhead and R.H. Wortman, "Systems Approach to Airfield Pavements" *Proceedings of the Allerton Park Conference*, (U.S. Army Construction Engineering Laboratory [CERL], [in publication]).

[2] E.L. Murphree, Jr., R.W. Woodhead, and R.H. Wortman, "Airfield Pavement Systems" *Transportation Engineering Journal of ASCE*, Vol 97, No. TE 3, Proc. Paper 8283, (August 1971), pp. 389-399.

Once the user matrix is established, each of the elements (users) is analyzed with respect to the aircraft/pavement interface to determine the functional requirements for airfield pavement systems. This process insures that the resulting set of user requirements is both comprehensive and accurate, and clearly demarcates requirements for each user.

After the users' requirements are determined, a hierarchy of users for airfield pavement systems is established. This ranking of the users not only facilitates the completion of the subsequent task of quantifying the requirements, but aids in distinguishing between the primary and secondary users. By insuring the satisfaction of the primary users, it is contended that the immediate requirements of the secondary users are also fulfilled.

A major task is that of quantifying descriptive user requirements. It entails converting each of the descriptive requirements into measurable quantities. For example, a pilot will require that a ride be smooth enough so that he can easily monitor his instrumentation. (This is defined as being able to obtain a nondistorted reading from a cockpit display, which is subject to vibration and acceleration exposures, resulting from the aircraft/pavement interactions.) Acceptable vibration and acceleration levels necessary for the pilot to read his instrumentation and perform the necessary functions with comfort and safety are determined. These tolerable levels of acceleration and vibration are considered to be one of the user requirements. In this manner, the comprehensive list of quantified requirements is generated.

Having developed the comprehensive list of user requirements, it remains for future studies to transform and correlate them with the aircraft pavement interaction model. For example, the roughness of a ride (as defined by the passenger, shipper, or pilot) must be correlated with the surface characteristics of the pavement. This can be accomplished, but will require the development of transfer equations which enable the various disciplines to communicate. These transfer equations will be employed to convert the user requirements into compatible terminology and to correlate the quantitative outputs from the aircraft, pavement, and user requirement models. A more coherent illustration of this problem is as follows: If a passenger opinion that the pavement was too rough is related through channels to a maintenance supervisor, the supervisor can neither accurately evaluate nor improve the ride. However, if it is determined that when a spe-

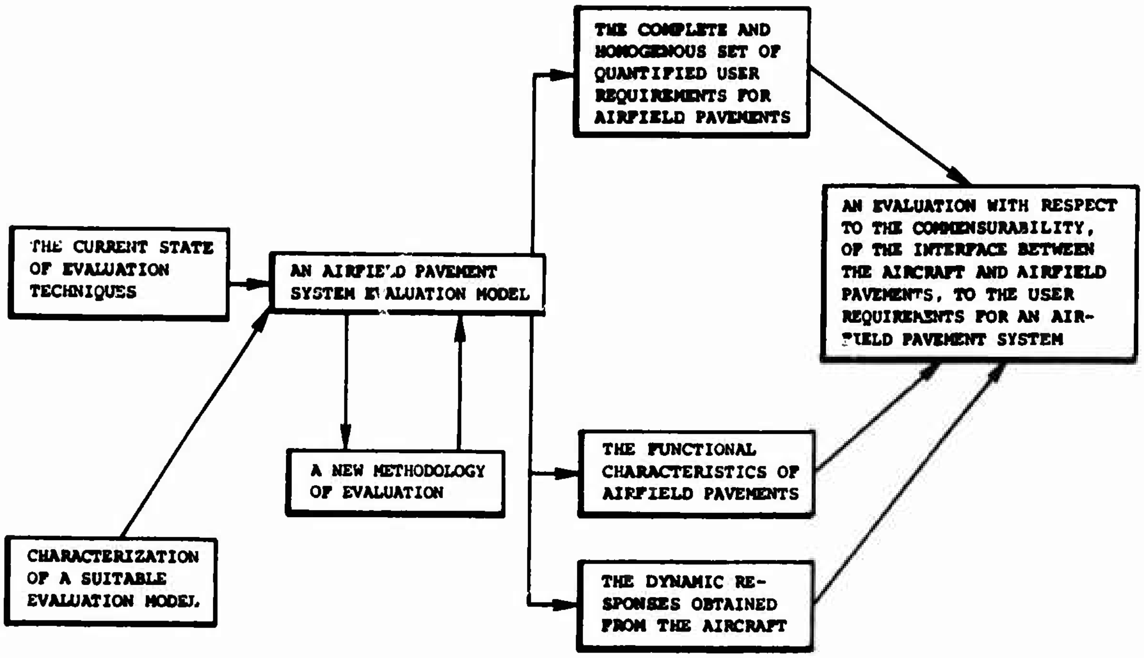

Figure 1. The pavement evaluation model.

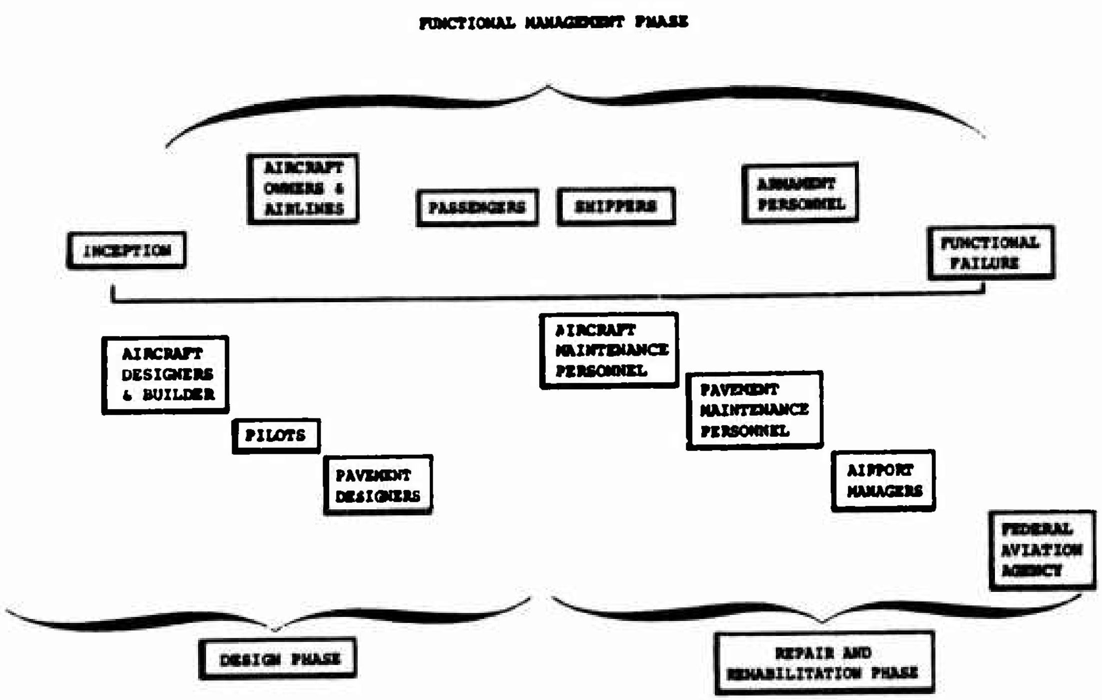

Figure 2. Airfield pavement system on a time spectrum.

cific aircraft passes over a pavement with a specific change in grade, at a specific speed, the passengers and cargo will experience a vertical acceleration of +0.3 G's,[3] the supervisor will then be able to recommend specific maintenance that must be accomplished in order to rectify the situation, and satisfy the passenger's needs.

Therefore, by defining the users and their requirements, quantifying these requirements, and transforming them into compatible terminology for airfield operators and maintenance personnel, a complete and homogenous set of quantified user requirements for airfield pavement systems is defined.

2 USERS OF THE AIRFIELD PAVEMENT SYSTEM

Users of an airfield pavement system can be identified by determining the categories of individuals that support the functional unit, which essentially consists of a pavement and an aircraft. This is accomplished by tracing the system from (1) its point of inception (the design phase), through (2) the functional or management phase, and (3) the rehabilitation phase. This procedure is shown in Figure 2.

In essence, the purpose of this diagram is to impose the development of the airfield pavement system on a time spectrum, where the users are the elements necessary for the growth of the system. By proceeding in this manner, the users will become readily apparent, and the complete list of users can be easily obtained.

The Process of Obtaining the Users. The inception of the airfield pavement system occurred with the development of the first aircraft. This generated the first two users: the aircraft designer, who required a landing strip that would impose minimum damage on the aircraft while facilitating its operation; and the pilot, who required a surface which would provide maximum control of the aircraft under ground roll conditions. As aircraft became more sophisticated, more sophisticated airfield pavements became necessary. This required the talents of another user: the pavement designer. Therefore, the design phase currently consists of the aircraft designer, the pavement designer, and the pilot, who unites the aircraft and the pavement to generate a functional unit.

This system as established can be utilized in many capacities. For example, it is essential for national defense, where aircraft armament personnel become users since they require satisfactory surfaces for the shipment of military "pay loads." Passengers and shippers also utilize the airfield pavement in the transportation of persons and goods. As the demand for air travel increases, the mix, volume, and frequency of traffic becomes a function of the aircraft owners and airlines, who in turn impose increasing requirements on the system.

Ultimately, repeated loads on the pavement cause a reduction in the functional capabilities of the system, and maintenance personnel are employed to restrict or alleviate this reduction. As the frequency and magnitude of loads increases, the possibility of a functional failure becomes greater, and the airport manager (or operator) must ensure that this portion of the airfield pavement system is maintained at a functional level. Finally, there is a user that is charged with: regulating air commerce to promote its safety and development; promoting, encouraging and developing civil aviation; developing and operating a common system of air traffic control for both civilian and military aircraft; and promoting the development of a national system of airports.[4] These tasks are accomplished by the Federal Aviation Administration.

The Complete Set of Users. The comprehensive list of users who impose functional requirements and restrictions on airfield pavement systems is as follows:

(1) Aircraft designers and manufacturers (Boeing, Lockheed, Beechcraft, etc.)
(2) Pavement designers and builders (Corps of Engineers, consultants, private contractors, etc.)
(3) Pilots (military, commercial and private pilots)
(4) Armament personnel (aircraft weapons specialists, etc.)
(5) Shippers (General Box Company, Western Electric, International Harvester, military, etc.)

[3] N.C. Yang, *Reports on Pavement Design and Tests, Redevelopment Program-Newark Airport* (The Engineering Department, The Port of New York Authority, June, 1967).

[4] *United States Government Organization Manual* 1970/71 (Office of the Federal Register, National Archives and Records Service, General Services Administration).

(6) Passengers (those seeking luxury and those simply seeking transportation)
(7) Aircraft owners and airline companies (private industry, Trans World Airlines, Pan Am., Air Force, etc.)
(8) Aircraft maintenance personnel (certified mechanics who are self employed, and those who work for aircraft owners)
(9) Pavement maintenance personnel (consulting firms, Corps of Engineers, base maintenance crews, and personnel hired by airfield owners or managers)
(10) Airport managers and operators (the individuals responsible for maintaining the airfield at a functional level)
(11) The Federal Aviation Agency.

Parts of this list may appear to be redundant, or one set of users may be a subset of another, but a complete list is necessary to ensure that the total field of users is covered. If the requirements specified by one user are identical to those specified by another, this will become evident when the actual requirements are developed in subsequent sections.

3 USER REQUIREMENTS FOR AN AIRFIELD PAVEMENT SYSTEM

Specific functions which must be provided by airfield pavements (i.e., the operational surface), are related to the needs of a user, and user requirements are connected with the interaction of the pavement and aircraft.

A user requirement requires the identification of the user, the user's viewpoint, a description of the current state of the system, and the next intended state of the system. Viewed in this manner, the requirement that pertains to the transformation of each user from one system state to the next will be portrayed. It is important to recognize at this point that a user requirement does not need to be a technical measure, but can be a qualitative statement of need. Such requirements will give direction to the technical measures which represent the requirements. It is, of course, vital that technical measures ultimately be developed for the user requirements, but initially the focus will be on the basic needs.

The Process of Obtaining User Requirements. Interactions between the aircraft and pavement involve not only the physical elements associated with the interface, but also the human factors which affect the crew and other occupants in the aircraft. Thus, all of the interactions which occur between the aircraft and the pavement during takeoff, landing, and ground operations are defined.

To develop these user requirements, the aircraft/pavement system is conceptualized as a series of user system states and state transformations. The number and type of users, states, and transformations are such that the entire facility operation and management is described by this representation. A diagram representing the states of the system is presented in Figure 3.

When the user is in this system, he can be in any one of the following states: parked, taxi, takeoff, aborted takeoff, airborne, aborted landing, or landing. The juxtaposition of the states gives the transformation required, and thus the basic user needs associated with each change can be determined. A user can be inserted in any state, and maneuvered through the system (from one state to another) while generating a requirement at each transformation.

For example, assume the passenger is the user and he is currently in the state of landing; the next desired state is that of being at taxi speed on the runway or pavement. The operational activity involved in going from one state (landing) to the other (taxiing) would be the deceleration of the aircraft. The success of this change in state could then be judged by the user in terms of safety, economy, efficiency or, simply, general acceptability.

The Subjective Set of Requirements. Employing the above process, the comprehensive set of requirements for the aircraft/pavement interface may be determined. The requirements for each category of user are described as follows:

(1) Aircraft designers require structural integrity of the aircraft (i.e., meeting the prescribed aircraft specification); and require geometric configurations and physical supports adequate to accommodate the physical size and weight of the aircraft.

(2) Pavement designers require structural integrity from the pavement, such that it will remain functional for its entire design life (i.e., resist deterioration while serving in the user-imposed environment).

(3) Pilots require adequate physical clearnance to maneuver the aircraft; minimal cockpit vibration, such that a high level of instrumen-

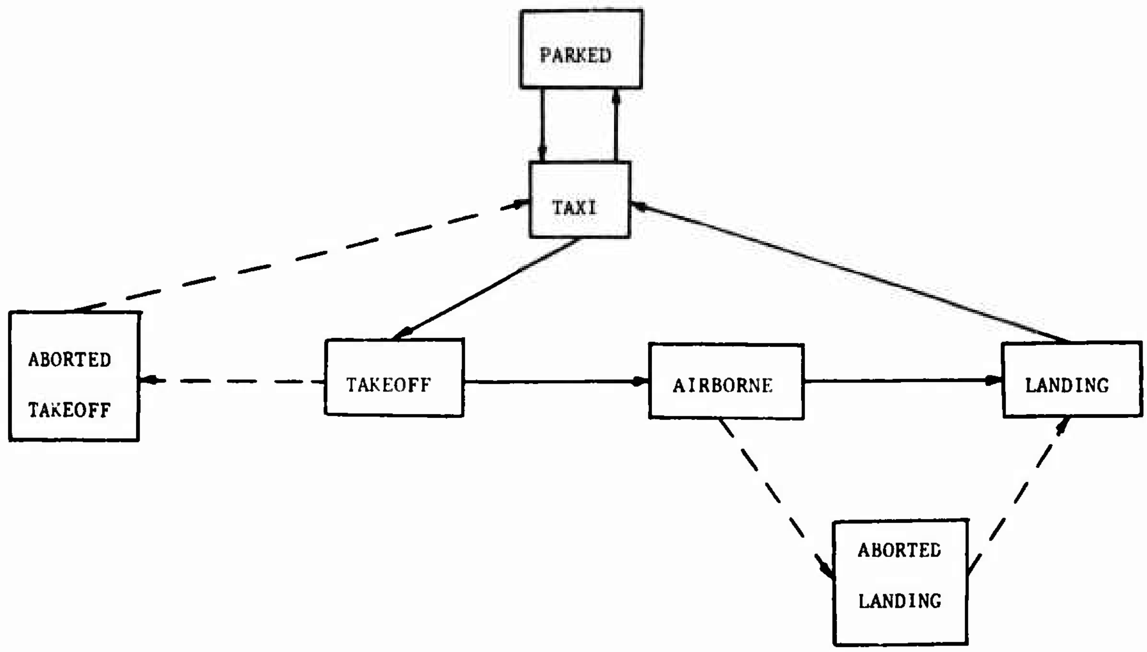

Figure 3. A diagrammatic presentation of the airfield pavement system.

tation readibility can be maintained; and as many takeoff and landing visual aids as possible.

(4) Armament personnel require sufficiently vibration-free transportation, as well as a satisfactory aircraft suspension system, so that the armaments will not be damaged while in transit.

(5) Shippers require that goods be transported without damage due to excessive vibrations or accelerations, and with minimal delay.

(6) Passengers desire comfort, minimum delay, and safety.

(7) Aircraft owners and airline companies desire a pavement system that will impose minimum damage on the aircraft and its contents, as well as expediting and facilitating their operation.

(8) Aircraft maintenance personnel desire a pavement system to assist in the effective operation of the aircraft, via minimum contamination on the pavement and smooth surface conditions.

(9) Pavement maintenance personnel desire to maintain the pavement in a functional state and to extend the pavement life (i.e., resistance to changes while in service under the user-imposed environment.)

(10) Airport operators and managers desire ease of maintenance and serviceability of their airfield pavements, such that all customers will consistently be satisfied, plus a geometric plan to facilitate traffic movement and regulation. (Note: a projected use profile of the user would be of great assistance in fulfilling this requirement.)

(11) The Federal Aviation Administration desires to regulate air commerce, to promote its safety and development, and to promote the development of a national system of airports.[5] (Again, a projected use profile would be of great assistance.)

While these statements itemize the individual user's requirements and desires for an airfield pavement system, there exist three requirements which all of the above users have in common: (1) safety, (2) economy, and (3) efficiency. In essence, if a functional unit of the aircraft/pavement interface is not safe, it will not be employed; if any unit is not economically feasible, it may have to be omitted; and if any facet of the system does not function efficiently within the system, it will have to be improved or modified before its in-

[5] *United States Government Organization Manual*

corporation into the operation. As a result, the above users will establish the parameters for the pavement system.

The Hierarchy of Users. In order to distinguish between the primary and secondary users, and to expedite the task of quantifying the essential requirements for an airfield system, a hierarchy of users has been established as shown in Figure 4. This hierarchy is divided into two distinct categories: (1) 'primary users,' who impose immediate requirements on the airfield pavement, and (2) 'secondary users,' who impose requirements on the system only as a consequence of the needs of the primary users.

Examination of the subjective requirements of the users would tend to suggest the following: (1) the passengers will impose the strictest tolerances on the acceleration limitations; (2) the pilot will impose the strictest tolerances on the vibration limitations; and (3) the aircraft designers, owners, and maintenance personnel will place the greatest demands on the physical support and geometric constraints of the airfield pavement. The complete hierarchy of users will be substantiated in the following section.

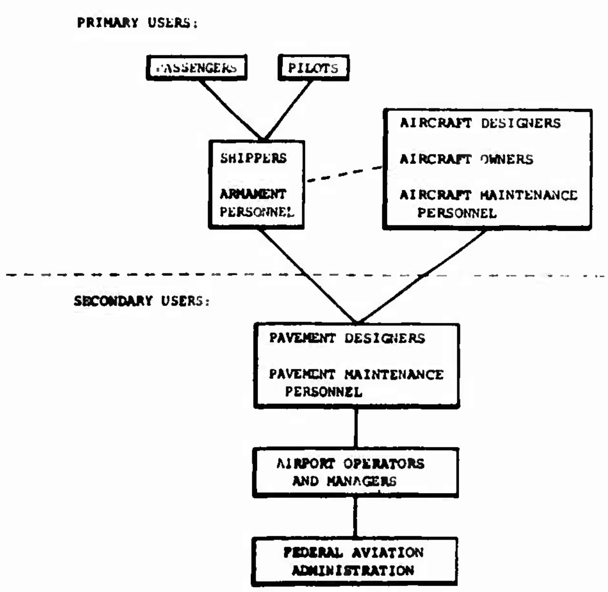

Figure 4. Hierarchy of users (in terms of their requirements of airfield pavements).

The shippers and armament personnel also impose primary requirements on the airfield pavement system, but not as stringent requirements as those of the pilot and passengers. Accelerations resulting from the interaction of the aircraft with the pavement pose little threat to these particular users when the spectrum of accelerations their products experience during other phases of shipment is considered.[6]

When the primary users are satisfied, it becomes the responsibility of the pavement personnel to insure that the pavement will continue to meet the functional requirements of those users. The pavement personnel also have definite requirements (that the pavement resist the user-imposed environment) which are not a primary demand but a supporting function. Therefore, this group has been classified as a secondary user.

Another set of users, the airport operators and managers, require that the pavement system be maintained at a functional level. In order to insure that the system is operational at a future point in time, the operators and managers need to be aware of the future characteristics and trends in air transportation. This requirement, to a certain extent, is shared by the Federal Aviation Administration, which desires a projected-use profile of the user. These are supplementary requirements, but are essential to the future of the system.

This hierarchy of users can be applied at any particular point in time, when the system is operational. However, it may vary with respect to accuracy over an extended period of time. For example: vibrations encountered when an aircraft makes one pass over a specified stretch of pavement may be acceptable to all users; but as the aircraft makes an increasing number of passes over the same stretch of pavement, the increased vibration exposure transmitted through the aircraft structure may become intolerable, as it may lead to structural damage of the aircraft.

Therefore, if the needs of the users at the upper portion of the hierarchy are fulfilled, the immediate requirements of the subsequent users are also satisfied. This will be further substantiated in the following section, in which requirements of the primary users are quantified. This does not preclude however, users

[6] T.J. Drummy, "Problems and Preventions of Shock Damage to Air Cargo," *Shock and Vibration Bulletin*, No. 9, pp. 35–61.

lower down in the hierarchy from influencing the user requirements and tradeoffs between such factors as floatation vs. pavement cross section.

4 QUANTIFICATION OF THE USER REQUIREMENTS

In this section, subjective requirements are stated in more explicit terminology, and delineated to take the form of measurable entities which can be incorporated into a format for the evaluation of airfield pavements. This will provide definite measures of the dynamic response requirements that will ultimately provide pavement personnel with a more exact set of dynamic constraint specifications for design and maintenance.

Requirements for each set of users are quantified individually to systematically designate parameters for the essential components of the system. Because of the great number of variables related to user requirements, many of these quantifications are presented in terms of graphs, charts, and diagrams.

Note that these quantifications consist primarily of the dynamic response tolerances for the various users. The other requirements are only mentioned, but adequate references are given for those who desire further information.

Requirements of the Passengers. Assuming the system to be safe, economical, and efficient, the primary passenger requirement for an aircraft/pavement system is comfort. Comfort is quantified in terms of the acceleration and vibration sensed by passengers in the aircraft.

Acceleration is produced by forces which must be developed through external energy sources or through interaction with the aircraft and pavement. The forces producing the accelerations may be either positive or negative. For example: for horizontal accelerations, during takeoff the aircraft has the need to accelerate to takeoff velocity from a static position; whereas during landing the vehicle must decelerate from a landing to a taxi speed. The expression of necessary forces in a concise, explicit manner (via acceleration levels of the aircraft), will form the basis of effective communication among several disciplines concerned with pavement performance.

Human tolerance to acceleration is a function of duration, magnitude and direction of the acceleration vector. The human tolerance levels to acceleration, for the various directions, are shown in Figures 5, 6, 7, and 8.[7] The lateral (side to side) acceleration tolerances are not given here, since the magnitude and duration of such accelerations encountered during the aircraft/pavement interaction are negligible.[8]

Vibration requirements consist of limits placed on the oscillation of the aircraft, resulting from the aircraft/pavement interaction. The oscillations may be defined as vertical (foot-to-head), longitudinal (front-to-back), or lateral (side-to-side). For example, when an aircraft with bicycle landing gear rolls along a pavement with long wave deviations in the pavment surface, the aircraft may begin to "porpoise," producing undesirable motions within the fuselage.

Many riding indices have been established. Figure 9 shows the comfort limits recommended by various investigators for vibrations along either the vertical or an unspecified axis.[9] As can be seen, the investigators do not agree on exact values for the tolerance levels.

The John Hopkins Applied Physics Laboratory has compiled riding comfort indices for each direction of vibration which approximate the mean values for the vibration tolerances that have been established in this field. These are individually displayed in Figures 10, 11, and 12.[10] The numbers on the Figures are to be interpreted as follows: less than 1.0 is excellent, 1.0–1.5 is good, 1.5–2.0 is normal, 2.0–3.0 is bad, and greater than 3.0 is unacceptable. Values from the curves generally agree with the results shown in Figure 9.

Many methods have been developed to assess man's reaction to vibration in a quantative manner, but most of these are based on a limited number, specific types, or a specific interpretation of experiments and tend to contradict each other in certain aspects. These results have been averaged and simplified, as shown in Figure 13. The figure shows the peak accelerations in three ranges in which subjects: perceive vibration (I)

[7] C. Harris and C. Crede (abstracted from: M. Eiband, NASA memo 5-10-59E), *Shock and Vibration Handbook* Vol 3 (McGraw-Hill, 1961).
[8] *Ibid.*
[9] R.M. Hanes, *Human Sensitivity to Whole-Body Vibration in Urban Transportation Systems: A Literature Review* (Johns Hopkins University, Applied Physics Laboratory, May 1970).
[10] *Ibid.*

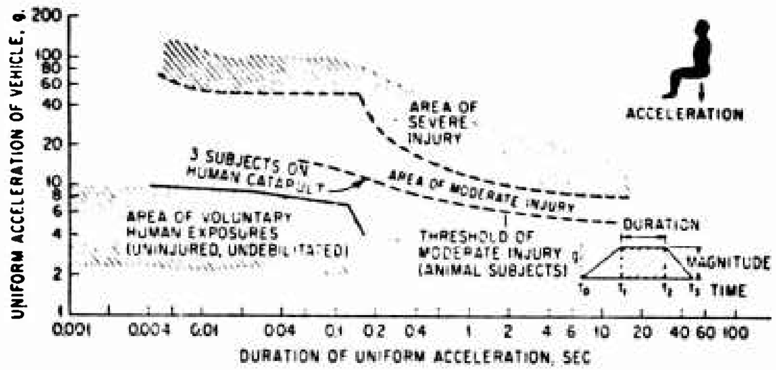

Figure 5. Tolerance to tailward acceleration.

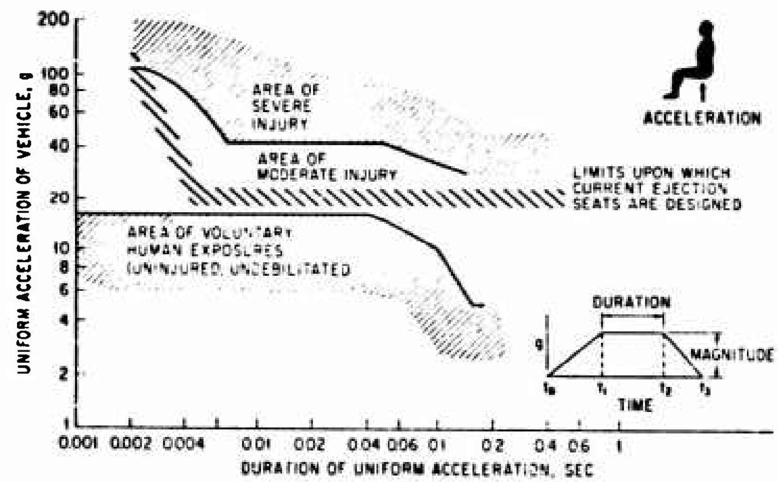

Figure 6. Tolerance to headward acceleration.

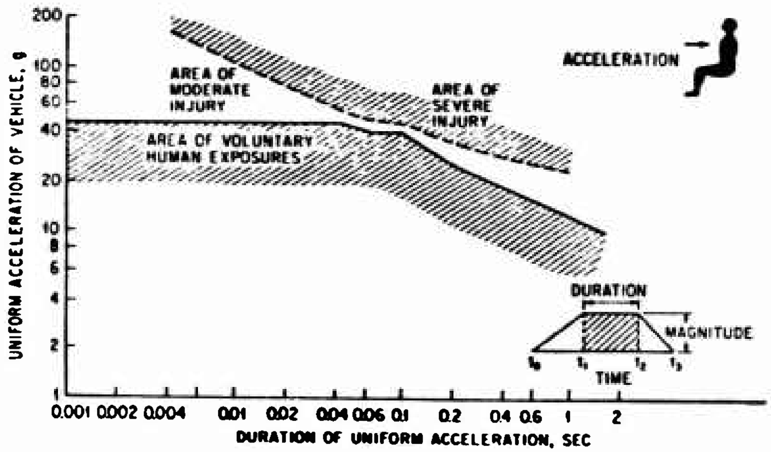

Figure 7. Tolerance to spineward acceleration.

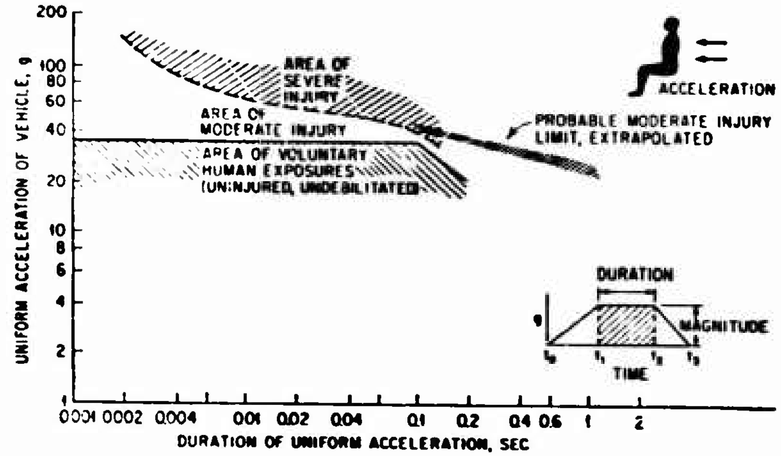

Figure 8. Tolerance to sternumward acceleration.

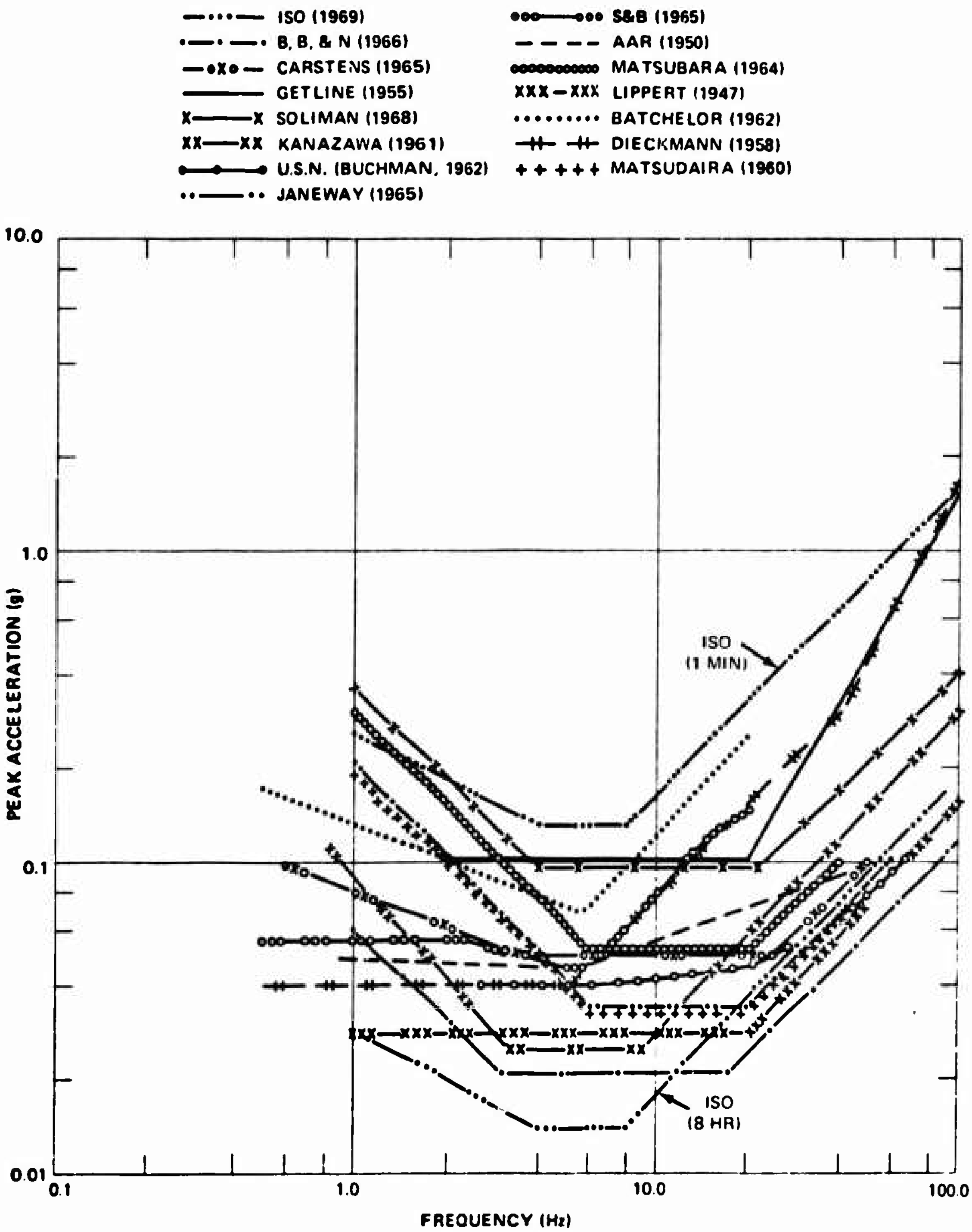

Figure 9. Recommended comfort limits.

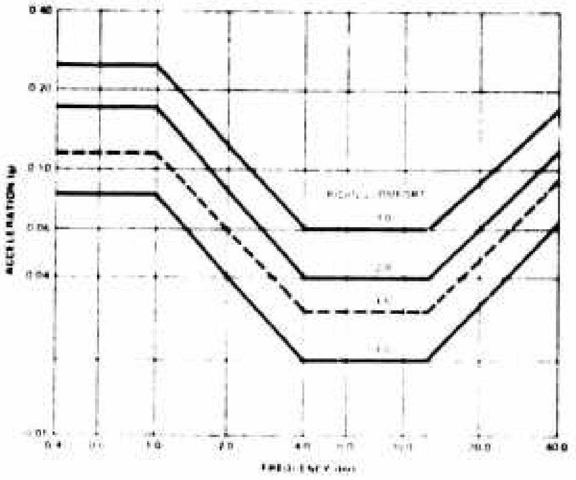

Figure 10. Lateral vibration tolerances.

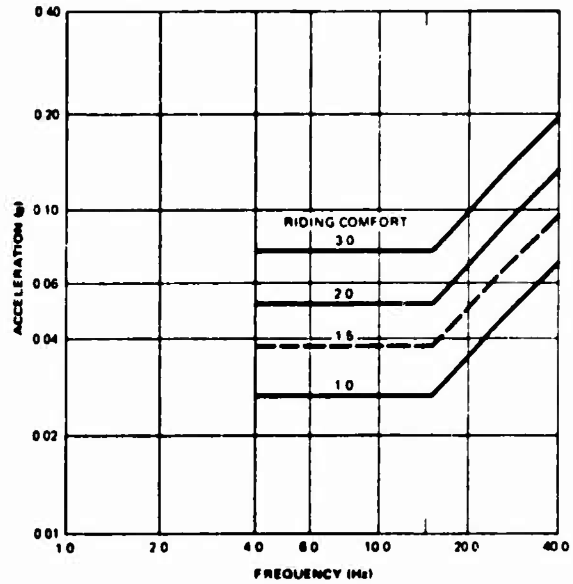

Figure 11. Longitudinal vibration tolerances.

find it unpleasant (II); refuse to tolerate it further (III). The shaded areas represent one standard deviation on either side of the mean.[11] These curves were developed from tests on subjects without any protection, and for exposure times of 5 to 20 minutes. The short time tolerance curve was developed from tests on subjects protected with standard Air Force lap belts and shoulder harnesses, with exposure times of approximately 1 minute. The "Vibration Tolerance Curve for Military Aircraft" was developed from data collected from exposure to vibration in military aircraft.

The criteria given in Figure 13 have been widely used to classify the severity of vibration exposure. They represent averages for the standing, sitting and lying positions. For vibrations in more than one direction, the vector sum of all components may be used as the acceleration stimulus in evaluating a given condition. Acclerations larger than those indicated by area III in Figure 13 probably can be tolerated without harmful effects for short time periods only by the

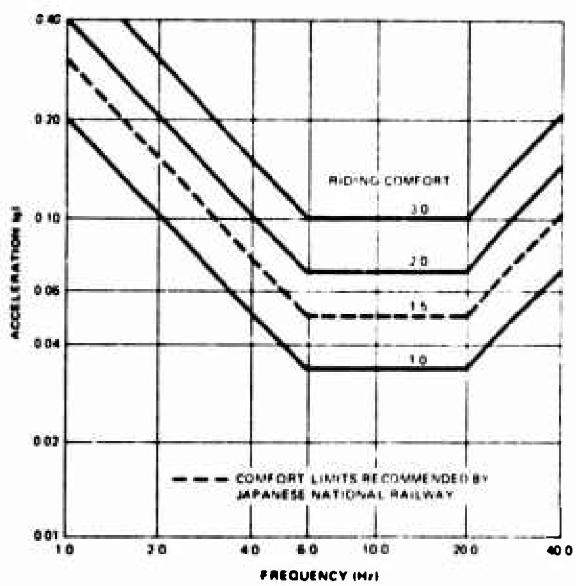

Figure 12. Vertical vibration tolerances.

[11]C. Harris and C. Crede (abstracted from D.E. Goldman, VSNMRI Rept. 1, NM 004 001, March 1948; G.L. Getline, Shock and Vibration Bull., 22, Suppl., Dept. of Defense, Washington, D.C., 1955; G. Zieglnrueker and E.B. Magid, USAF, WADC Tech. Rept. 59 18, 1959; R.T. Fibikar, Prod. Eng. 27: 177, November 1965; G. von Bekesy, Z. Akust, 4: 316, 1959).

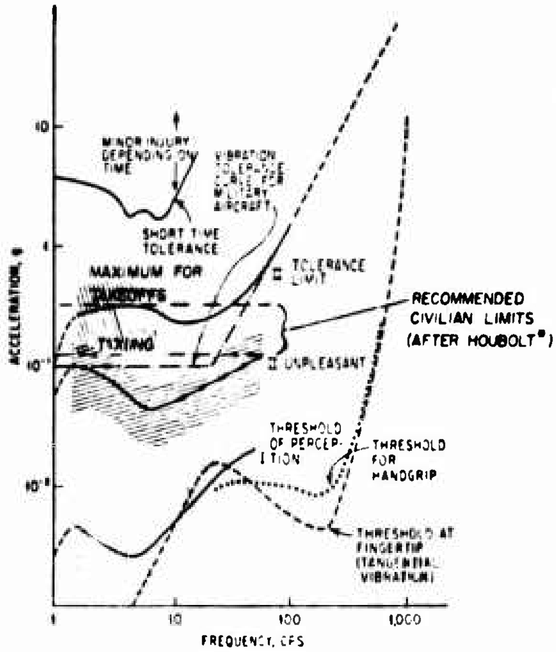

Figure 13. Vibration tolerance criteria.

majority of young male subjects. The curve marked "short time tolerance" applies to exposure times on the order of 1 minute or less for young, male military subjects strapped in an airplane seat. This curve represents the lower boundary at which physical tissue damage occurs with relatively short exposure times.[12]

Requirements of the Pilots. User requirements by pilots for an airfield pavement system are: (1) adequate runway length, (2) sufficient stopping capability and controlability of the aircraft, (3) minimal cockpit vibration, and (4) as many visual takeoff and landing aids as possible. The pilots also desire adequate support and physical clearance for the aircraft; these will not be quantified in this report, but the pertinent literature will be cited. An attempt to quantify the pilot's requirements is presented, but due to the vast amount of data published on this topic, the survey is neither exhaustive nor conclusive.

Runway length is directly related to the specific aircraft and use profile. The takeoff and landing requirements for the aircraft must be known in order to derive the necessary runway length.

For airports designed to serve general aviation, it is possible to group aircraft generally by their function. This permits determining a runway length even though the specific aircraft which will be using the facility is not known. If specific aircraft are used as a basis for design, more precise runway length determinations can be made. Some attempts have been made to list the required lengths for specific aircraft.[13] Such a listing established by the Air Force Weapons Laboratory is shown in Table 1.[14] *Jane's All the World's Aircraft,*[15] which is updated annually, also presents similar information, but in some instances gives somewhat different values than shown in Table 1. To determine the actual distance required for takeoff or landing requires knowledge of the type of aircraft as well as data for the following variables: (1) configuration of the aircraft, (2) pressure altitude of the airfield, (3) velocity and direction of the wind with respect to the ground path of the aircraft (4) gross weight of the aircraft at the time of landing or takeoff, (5) slope of the runway, and (6) air temperature at the airfield site. Thus more exact and applicable distances can be obtained by imposing the values for these variables on the specific aircraft performance curves.[16] Performance curves are included in the respective flight manuals for each aircraft and can be secured from the aircraft manufacturers. The performance curves for the majority of the aircraft have been compiled in a Federal Aviation Administration publication.[17]

Controlability of the aircraft during taxiing, takeoff and landing is another factor pertinent to the pilot's requirements. Currently the only method of evaluating control in terms of the aircraft/pavement interface is a measure of the coefficient of friction. The coefficient of friction is reported by civilian installations in terms of "IACO ratings,"[18] and by the mili-

* J.C. Houbolt, "Runway Roughness Studies in the Aeronautical Field," *ASCE Transactions*, Vol 126, Part IV (1962) p. 427.

[12] *Ibid.*

[13] *Pertinent Characteristics of Military Aircraft*, Miscellaneous Paper No. 5-1 (Ohio River Division Laboratories, Corps of Engineers, July 1964).

[14] DeLynn R. Hay, *Aircraft Characteristics for Airfield Pavement Design and Evaluation*, Technical Report No. AFWL-TR-69-54 (Air Force Weapons Laboratory, Kirtland A.F.B., October 1969).

[15] *Jane's All the World's Aircraft* (S. Low, Marston and Company, Limited, London, 1971).

[16] *Flight Manual, USAF Series T-29B, C, D Aircraft, T.O. 1T-29A-1 Performance Data* (January 1970), p. 2A3 7.

[17] *Runway Length Requirements for Airport Design* AC 150/5325-4 (April 1965).

[18] *Flight Manual, USAF Series T-29B, C, D Aircraft, T.O. 1T-29A-1, Performance Data* (January 1970), pp. 2A3 7.

Table 1
Aircraft Performance Requirements

Aircraft	Takeoff Distance* (ft)	Takeoff Distance** (ft)	Landing Distance** (ft)	Landing Distance* (ft)
A-7D	5800	7800	3950	4950
A-26A	4075	4800	2390	3390
A-37B	1590	2480	1380	2950
B-47E	10,400	12,000	4600	5500
B-52H	6160	8120	2370	4480
B-57B	5000	6200	2350	3100
RB-57F	2600	2800	2800	4450
B-58A	7850	13,700	2615	5285
RB-66A	6750	9350	3595	4915
FB-111A		Data Classified	–	–
F-4E	2940	3580	3[illegible]00	4370
F-5A	6050	8100	3550	5400
F-86H	2310	3510	2950	3900
F-89J	3950	5700	2960	4130
F-100C	4175	6150	4080	5500
F-100F	5500	8200	4620	5180
RF-101H	3380	4630	4225	5170
F-102A	2290	3800	2500	5160
F-104G	5300	7930	2900	4590
F-105F	4650	6500	4600	6370
F-106B	2820	4540	4530	5970
F-111A	4400	5500	1700	2400
C-5A	6020	6910	2175	3360
C-7A	725	1200	825	1770
C-8A	1560	2200	900	1575
C-9A	4380	5360	1756	2690
C-10A	2330	3220	1325	2490
C-47D	2900	5100	2040	3210
C-54G	2780	5780	1918	3170
KC-97G	6500	8150	3390	4690
KC-97L	4600	5850	1590	2725
C-118A	4350	5500	2500	3400
C-119G	3180	5470	2236	3270
AC-119K	2310	3700	2156	3097
C-121G	4030	5080	2660	3780
C-123K	1810	2802	1072	1797
C-124C	5520	7380	3200	4525
C-130E	3600	5275	4150	5660
HC-130H	3170	4650	1840	2875
C-131E	3580	5150	1770	2650
C-133B	5040	5640	4385	6160
C-135A	7200	8530	3470	5205
KC-135A	10,200	12,840	1970	3390
C-140A	3670	5150	2050	2980
C-141A	2490	3360	1620	3480

*Ground Roll
**To clear a 50-ft. obstacle

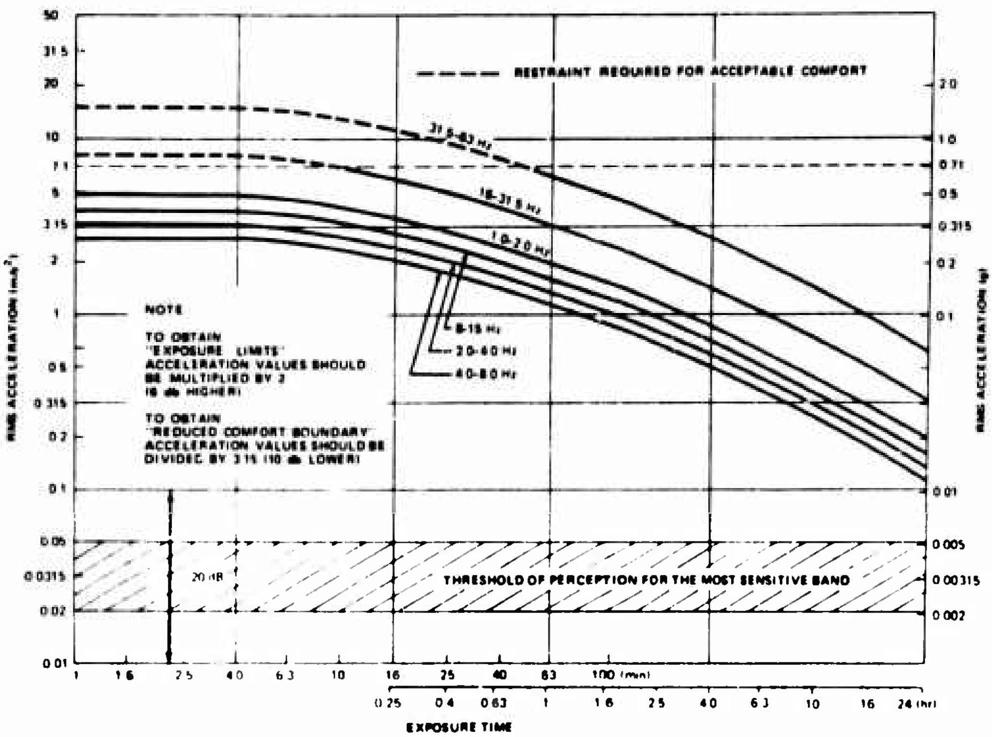

Figure 14. Proposed standards for vibration.

the root-mean-square normal accelerations in the pilot compartment of the turbojet airplane exceeded those at the center of gravity by from 45 to 110 percent.[27] This may indicate that the roughness requirements prescribed by the pilot will consistently impose the most stringent tolerances on the vibration parameters.

Requirements of the Aircraft Designer, Aircraft Maintenance Personnel, Aircraft Owners, and Airline Companies. The primary requirement of the aircraft maintenance personnel is for structural integrity and continued functionality of the aircraft. This essentially imposes the following demands on the pavement system: (1) a smooth pavement surface, (2) pavement strength sufficient to support the number of aircraft operations anticipated over the design life, (3) physical clearance (i.e., adequate maneuvering space), and (4) minimum foreign object damage from the pavement surface and adjacent areas.

A smooth pavement surface has been defined as one which, when interfaced with an aircraft, results in minimum acceleration forces being imposed on the aircraft and its contents. Consequently, aircraft personnel requirements will be satisfied (with respect to roughness) if the acceleration and vibration exposures are such that the structure of the aircraft is not exposed to limits that may impose structural damage. NASA has collected these structural requirements specifying acceleration tolerances for a number of aircraft. Examples of these requirements are given for a propeller-driven aircraft (C-123), a turbojet-driven aircraft (C-130), and a jet-propelled aircraft (KC-135), in Figures 15, 16 and 17 respectively.[28]

Comparing these acceleration parameters with those specified by the passenger or the pilot, it is apparent that the tolerances imposed by the aircraft personnel are much less restrictive than those imposed by the pilots and passengers. Those tolerances may be-

[27] G.J. Morris, *Response of a Turbojet and a Piston-Engine Transport Airplane to Runway Roughness*, NASA Technical Note TN D-3161 (December 1965).

[28] *Transportation Shock and Vibration Design Criteria Manual*, NASA-CR-77220, Vol 1 (September 1965).

tary in terms of "R.C.R. readings."[19,20]

Pilots also desire as many visual aids as possible for landing, takeoff, and taxi. These requirements have been quantified and can be found in the appropriate FAA specification documents.[21] Further recommendations for visual aids have been prepared by the Airline Pilots Association.[22]

An investigation was conducted by the Ames Research Center, National Aeronautics and Space Administration, and the Aviation Medical Acceleration Laboratory, Naval Air Development Center, to study the effects of acceleration on pilot performance and to obtain data for use in establishing tolerance to acceleration. Results of this study demonstrated that a well-trained subject can accomplish control tasks during moderately high accelerations for prolonged periods of time. The maximum level of acceleration tolerated was approximately six times that of gravity for approximately six minutes, though this result varied slightly with acceleration direction.[23] These findings quantify the pilot's tolerances for acceleration, which are less stringent than those of the passengers. Therefore, if the parameters specified by the passengers are met, the pilot's acceleration tolerance requirements are also satisfied.

A sustained acceleration, which does not affect the pilot's performance, per se, may be quite detrimental when cycled at specific frequencies. This may result from resonant responses of the aircraft components which decrease the pilot's performance on certain activities such as visual acuity and tracking tasks. Requirements for vibration tolerances have been quantified by the International Organization for Standardization, and are presented in Figure 14. This graph represents the recommended vibration criteria for working efficiency (including visual acuity and tracking tasks) as a function of exposure time.[24] These standards apply chiefly to the condition in which vibrations are transmitted to the body as a whole, through the supporting surface (the feet of a standing man, the buttocks of a seated man, or the supporting area of a reclining man). These limits are based upon data from both practical experience and laboratory experimentation. At present, no accepted standards exist.

Within a specified frequency range, the curves in Figure 14 are applicable to periodic vibrations, to random or nonperiodic vibration with a distributed frequency spectrum, and, provisionally, to continuous shock-type excitation. Recommended limits are provided for the following three criteria (both horizontal and vertical axes): (1) preservation of comfort (reduced comfort boundary), (2) preservation of working efficiency (fatigue decreased proficiency boundary), and (3) preservation of health or safety (exposure limit).

"For vertical vibration, when a peak acceleration of approximately 1 g is exceeded, the recommendation can only apply meaningfully to the restrained subject. For horizontal vibrations (i.e., longitudinal and lateral), the above limits are to be lowered by a factor of the square root of 1/2. For vibrations in more than one direction simultaneously, the corresponding limits apply to each axial component."[25] For vibration containing more than one discrete frequency, each component is evaluated ". . . in the same manner with reference to the appropriate limit at the frequency of that component."[26] With respect to angular (roll, pitch and yaw) vibrations, the center of rotation can often be assumed to be far enough from the point of application of vibration to the body for the resulting motion to be approximated by linear vibration alone.

NASA conducted an investigation at the Langley Research Center to determine the response characteristics of a turbojet airplane and a piston-engine transport airplane on runways having different roughness characteristics. In this study, it was determined that

[19] Thomas J. Yager, W. Pelham Phillips, Walter B. Horne, and Howard C. Sparks, *A Comparison of Aircraft and Ground Vehicle Stopping Performance on Dry, Wet, Flooded, Slush-, Snow-, and Ice-Covered Runways*, NASA-TND 6098, AD 715 943 (November 1970).

[20] *A Comparison of Wet and Dry Stopping Distances on Several Runway Surfaces Using an Aircraft and a Diagonal-Braked Automobile*, ASD-TR-69-117, AD 871 468 (Aeronautical Systems Division, Patterson A.F.B., Ohio, April 1970).

[21] *Standard Specifications for Construction of Airports*, (Department of Transportation, Federal Aviation Administration, May 1968).

[22] J.W. Meek, P.G. Perry, W.T. Alford, *ALPA Guide for Airport Standards* (Airline Pilots Association Airport Committee, Washington, D.C.).

[23] B. Creer, H. Smedal, and R. Wingrove, *Centrifuge Study of Pilot Tolerance to Acceleration and Effects of Acceleration on Pilot Performance*, NASA Technical Note D-337, AD 247 140 (December 1960).

[24] R.M. Hanes (abstracted from. International Organization for Standardization, Technical Committee 108, *Guide for the Evaluation of Human Exposure to Whole-Body Vibration*, ISO/TC 108/WG 7 [Secr.-17] December 1968, [unpublished]).

[25] *Ibid.*

[26] *Ibid.*

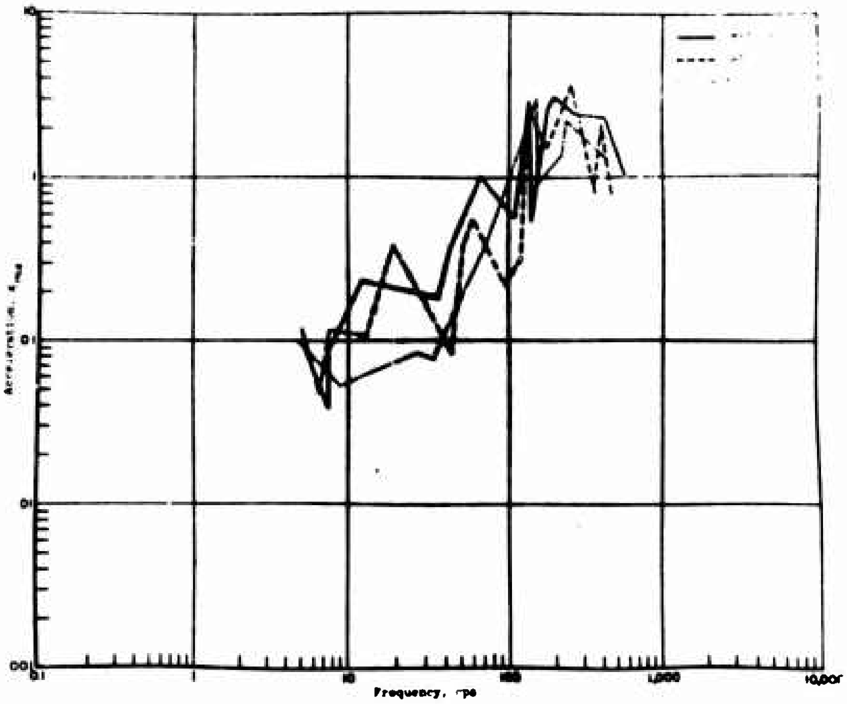

Figure 15. Acceleration envelope C-123.

come more rigid as an aircraft makes an increasing number of landings and takeoffs, but this will not be considered herein since no significant data are available to substantiate the magnitude of the problem.

One of the basic functions of the pavement is to provide physical support for the aircraft during the period when it is not fully airborne. This physical support should be capable of withstanding the static, dynamic and impact loading of the aircraft, plus the stresses and strains induced by environmental conditions existing at the site.[29]

Regardless of the type of pavement under consideration – rigid, flexible, prefabricated (landing mat), or bare soil – certain essential data, such as gear configuration, static wheel load, tire pressure, etc., are needed for the design or analysis of the pavement system. Reference tables which present aircraft dimensions, gross weights, performance data, landing gear configuration and other data necessary for such design and analysis have been published by the Army Corps of Engineers,[30] the Air Force Weapons Laboratory,[31] and the Federal Aviation Administration.[32] These data, as well as guidelines for their use, can be secured from their respective sources. The information presented does not give the quantified requirements for airfield pavements as dictated by aircraft maintenance personnel, as there are no data available correlating pavement structural distress with aircraft maintenance requirements. Even though the aircraft designers or owners may provide all the specifications for a particular aircraft, these will probably not define the dynamic or impact load that the aircraft will impose on the supporting surface. Transfer functions are needed to quantify the pavement response and functional requirements in more specific terms.

The physical dimensions of the aircraft impose certain requirements on the pavement which are re-

[29] E.J. Barenberg, "State of the Art Report on Mathematical Modeling of Pavement Systems," *Proceedings of the Allerton Park Conference* (U.S. Army Construction Engineering Research Laboratory, [in publication]).

[30] *Pertinent Characteristics of Military Aircraft*, Miscellaneous Paper No. 5-1 (Ohio River Division Laboratories, July 1964).

[31] D.R. Hay, *Aircraft Characteristics for Airfield Pavement Design and Evaluation*, Technical Report No. AFWL-TR-69-54 (Air Force Weapons Laboratory, October 1969).

[32] *Aircraft Data*, AC 150/5325-5A (Department of Transportation, Federal Aviation Administration, January 1968).

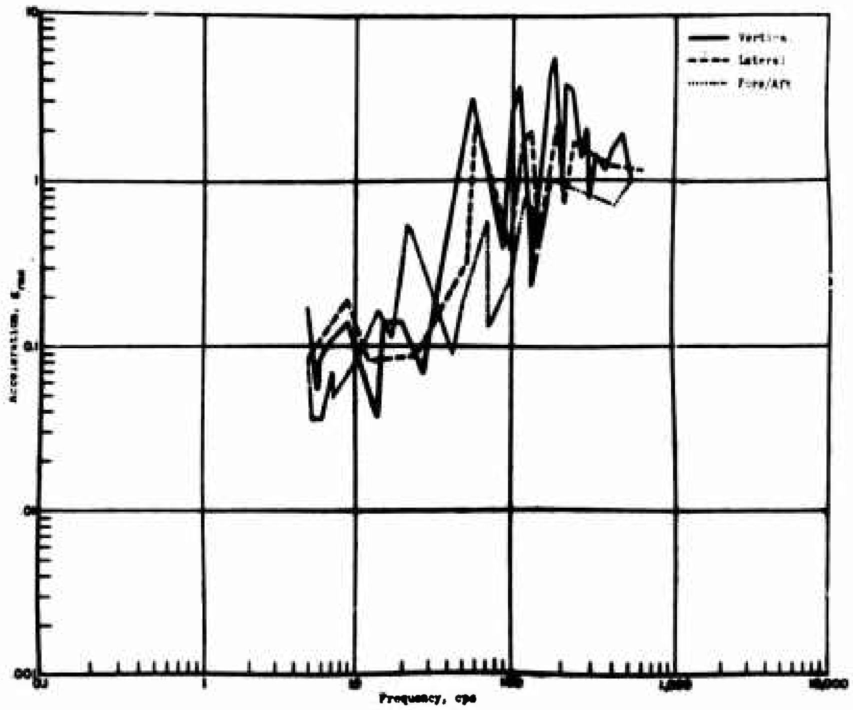

Figure 16. Acceleration envelope – C-130.

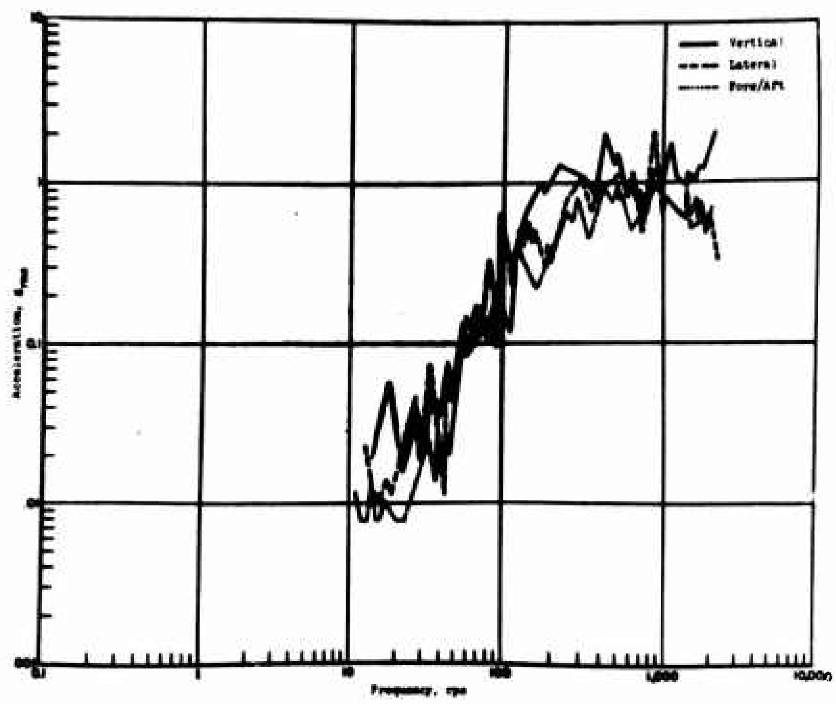

Figure 17. Acceleration envelope – KC-135.

flected in its geometric configuration. These are defined in terms of physical clearance and adequate maneuvering space. The quantification of requirements imposed by aircraft personnel for aircraft clearance and airfield pavement geometry have been published by the Airline Pilots Association,[33] and the Federal Aviation Administration.[34]

Finally, aircraft personnel require that the pavement surface and adjacent areas remain clear of all foreign objects, debris, and snow. This requirement has also been quantified by the Airline Pilots Association.[35]

Requirements of Shippers and Armament Personnel. Conversion by major air carriers to turboprop and turbojet aircraft, which began in 1957, has had an effect on the air cargo industry. The baggage compartments of these combination passenger-cargo aircraft have several times the carrying capacity of like compartments in piston-driven aircraft. These combination aircraft have continued to maintain an important role in the total supply of air cargo transportation, and many of the large aircraft have been converted for all-cargo operations. During 1962 over 950,000 tons of domestic cargo was shipped via aircraft. Thus shippers must be considered as primary users of the airfield pavement system.

Personnel associated with the shipment of cargo by aircraft have not imposed any tolerances for the vibration or acceleration levels resulting from the aircraft/pavement interaction. In January 1971, engineers from the U.S. Army Construction Engineering Laboratory in Champaign interviewed shipping companies and armament personnel in an attempt to secure these tolerances. It was determined that military armament and cargo containers were so designed that their tolerances for accelerations and vibrations were consistently more lenient than those of the pilots and passengers. Reasons for these findings become readily apparent by examining Figure 18, which shows comparisons of the average shocks recorded during a test shipment with the mean maximum shocks recorded during flight.[36] Obviously, the armament and shipping containers were designed to withstand accelerations during handling,

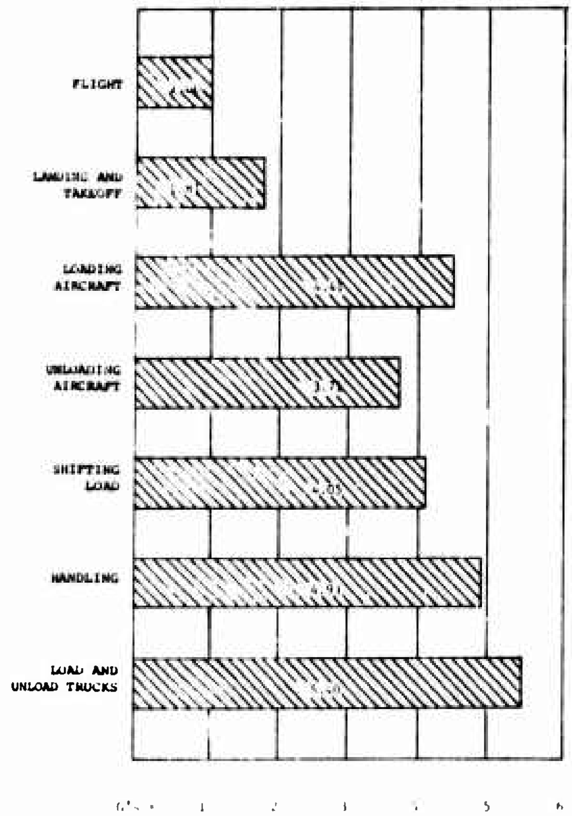

Figure 18. A comparison of the mean maximum shocks recorded during a test shipment with the average maximum recorded shocks during flight.

but not accelerations experienced while in the aircraft. When the handling facilities are improved, the shippers and armament personnel may then assume a more significant role in defining the user requirements for the system.

The shippers' greatest demand is for a pavement system that will expedite the movement of their goods, and thereby avoid delay. The best procedure for accomplishing this (with respect to the pavement system) is to insure that the pavement is maintained at a functional level, and will be serviceable for a substantial portion of the time.

Requirements of Pavement Designers and Pavement Maintenance Personnel. The importance of the various interrelated features of contemporary and future airports cannot be overemphasized. Planning and design must give equal consideration to present needs and fu-

[33] J.W. Meek et al.
[34] *Airport Design Standards Airports Served by Air Carriers-Taxiways*, (Department of Transportation, Federal Aviation Administration, May 1970).
[35] J.W. Meek et al.
[36] T.J. Drummy, pp. 35–61.

ture use. It is incumbent upon the designer to look to the potential, as well as the current, airport mission.

The inclusion of user requirements in airfield pavements in the design and evaluation process is directly associated with the pavement serviceability performance concept. Serviceability reflects the quality or level of service provided to the user of the pavement. The concepts associated with pavement serviceability and performance were set forth in an attempt to consider user needs during the pavement design and evaluation processes.

The primary requirement of these secondary users of airfield pavements is for structural integrity and high performance levels. More generally, this can be stated as: resistance to change under the user-imposed environment. The pavement designer is responsible for meeting the requirements of the primary users, but looks to the airport operators and managers, as well as the Federal Aviation Administration, for future trends. However, pavement maintenance personnel must compensate for all the pavement damage resulting from environmental stresses and from variations in the load, mix, volume, and frequency. It is desirable to have maintenance-free pavements, but at the present time, such pavement systems have not been developed. Better mathematical models for pavement systems are needed, not only to assist the designer, but also to guide the maintenance of these surfaces.

Personnel involved with pavement design and management ultimately require a definition of "functional failure" for airfield pavements. Under current definition a functional failure occurs when the pavement can no longer fulfill the requirements specified by the user. This is obviously too vague and general for application to specific design and management solutions.

Presently, pavement engineers simply seek to decrease the rate of pavement distress by minimizing the detrimental effects imposed by aircraft[37] and environment, without evaluating the relative return received for alternate design and maintenance strategies. Since no explicit rules exist for airfield pavement maintenance management, pavement engineers are compelled to follow corrective rather than preventive maintenance practices.

Requirements of Airport Operators and Managers. Users of airfield pavements require that the pavements be available for use under all reasonable conditions, and that they be maintained at a functional level as determined by the user requirements. The level of service required to maintain the pavement at a specified functional level may vary with changes in the aircraft or mission of the user. Thus, pavement designers must consider possible future use and changes in user requirements. Consequently, the primary requirement of the airport operators and managers is to consistently satisfy all users while providing minimum maintenance and servicing to the pavement system. To systematically accomplish this objective, it is essential for the operator or manager to establish a projected use profile. Trends in aviation have been cited,[38] but the most comprehensive set of aircraft characteristics, trends, and growth projections has been compiled by the Aerospace Industries of America.[39]

5 SUMMARY

Presented in this report is a listing of the airport pavement users and a set of quantified user requirements intended for use in the evaluation model. It was determined that there are essentially 11 categories of users for the airfield pavement system, and that these users could be classified in one of two major categories – primary or secondary. The primary users–consisting of the passengers, pilots, shippers, armament personnel and aircraft designers–exhibit definite needs for a pavement system, and thereby impose the primary requirements. The secondary users–consisting of the pavement designer, pavement maintenance personnel and airport operators and managers–also impose requirements, but only as a consequence of the demands of the primary users.

Therefore, the majority of the tolerances for the system are specified by the primary users. The strictest tolerances for accelerations are imposed by the passenger (Figure 13), and the strictest tolerances for vibrations are imposed by the pilot (Figure 14). Specifications for runway length, coefficient of friction, and visual aids for takeoff and landing are also prescribed by the pilot. The aircraft personnel will define the

[37] *Effects of Jet Blast*, AC 150/5325-6 (Department of Transportation, Federal Aviation Administration, April 1965).

[38] W. Wilks, *Technology Forecasts and Technology Surveys* (PWG Pub. Co., June 1971).

[39] *CTOL Transport Aircraft Characteristics, Trends, and Growth Projections*, (Transport Aircraft Council, Aerospace Industries of America, Inc., April 1970).

parameters for pavement strength, pavement geometries (physical clearance), and the amount of contamination on the surface of the pavement. The shippers, who are definitely primary users, impose no significant limits on the pavement system at present (Figure 18).

The secondary users also exhibit definite requirements, but not of the pavement system, per se. The pavement personnel show a definite need for a practical mathematical model of the pavement, and a transfer equation that will assist them in interpreting the user requirements. The basic request of the airport operators and managers (with respect to the pavement system) is for a "projected use profile," as defined earlier.

This report has set forth the quantified user requirements for an airfield pavement system by specifying (or providing the means for obtaining) the definite limits for the various elements of the system. However, input from other areas is still needed before these specifications can be fully used. These are:

(1) An aircraft dynamic response model which will take into consideration the effects of engine thrust and aerodynamic forces, as well as the surface shape and characteristics.

(2) An airfield pavement model that will consist of a stochastic model and, above all, a transfer equation for the evaluation of the actual pavement system (the aircraft/pavement interface).

GLOSSARY

This section defines the terms used throughout this report.

Acceleration – the rate at which velocity is changing with time; acceleration equals the change in velocity, divided by the time of the change, expressed in terms of gravitational forces (G's).

Airport – any area of land or water used, or intended for use, for landing and takeoff of aircraft, and any appurtenant areas used, or intended for use, for airport buildings and facilities located thereon.[40] (This word will be considered synonymous with the word *airfield*).

[40] *Standard Specifications for Construction of Airports* (Department of Transportation, Federal Aviation Administration, May 1968).

Amplitude – the maximum excursion of a vibrating body from its mean position.

Designer – one who conceives, draws the plans for, and executes the plans for a project or structure, such as aircraft designer or pavement designer.

Engineer – an individual duly authorized by the owner or sponsor, acting directly or through an assistant or representative, who, by training or experience, is qualified to make engineering decisions.

Frequency – the number of complete oscillations of a vibrating body per unit of time.

Functional Failure – the inability of the structure to fulfill the requirements imposed on it.

Gravitational Force (g) – A unit of measure for acceleration. One "g" is equivalent to (32 ft./sec.)^2

Landing Strip – any portion of the usable area of an airport which is suitable for the landing and taking off of aircraft under favorable weather conditions.

Operator – one who is responsible for the successful operation of a facility. His duties include patron satisfaction, as well as the maintenance and serviceability of the facility.

Owner – any public or private agency which, either individually or jointly with one or more agencies, is responsible for the operation of the facility.

Passenger – a traveler in a public or private aircraft.

Pavement – the combined surface, base, and subbase courses, along with the prepared subgrade, considered as a single unit.

Pilot – a person who is qualified and licensed to operate an aircraft.

Requirement – an essential requisite for the successful fulfillment of a function or mission.

Runway – that paved portion of an airport (usually instrumented) specifically used for the landing and takeoff of aircraft.

Shipper – one who transports commodities via any form of conveyance. This study will assume the primary means of conveyance to be an aircraft.

Shoulders – that portion of the runway or taxiway, paved or unpaved, adjacent to the trafficked areas, but not intended to carry normal aircraft traffic.

Specifications – the directions, provisions, and require-

ments contained therein, supplemented by special provisions, pertaining to the method and manner of performing the work, or to the quantities or qualities of materials to be furnished under the contract.[41]

Subgrade – soil which forms the pavement foundation.[42]

Surfacing – the top layer of the pavement.[43]

System – a regularly interacting or interdependent group of components forming a unified whole, which can be considered as a functional unit.

Taxiway – a paved or unpaved strip over which aircraft may taxi to and from the landing areas or parking areas of an airport.

User – one who imposes a requirement on any functional unit within a specified system.

Vibration – a periodic motion of the particles of an elastic body or medium in alternately opposite directions from the position of equilibrium when that equilibrium has been disturbed.

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[41] *Standard Specification for Construction of Airports*
[42] *Ibid.*
[43] *Ibid.*

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